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ABSTRACT

Mobile satellite (MSAT) technology is the basis for a new component of the telecommunications industry capable of providing services to small inexpensive subscriber terminals located almost any place in the world. The market for MSAT space segment capacity (bandwidth and power) is a natural monopoly that can be logically and technically distinguished from the market for MSAT services. The production of services relies on satellite power and bandwidth as factor inputs. From a social welfare perspective it is advantageous that the market for services be competitive to generate incentives for firms to probe the cost and demand surfaces of the service space. The demand for services is defined by subscriber choices in two distinct markets. The initial choice involves the selection of a terminal, determined by a tradeoff between price, functionality, and the price of usage, which may vary for terminal types. The subscriber then chooses among service offerings subject to the constraints imposed by the technical attributes of the terminal. The "physical" layer service standards, which specify terminal antenna gain, modulation, and error-correction coding, are evaluated in an engineering-economic analysis that models the variable cost of producing basic communications capacity. The demand for MSAT is considered in two parts: a reservation price for the subscriber terminal and the demand for usage. The demand for usage is a function of a vector of quality attribute variables. Of these, channel throughput (measured in bits per second), because of its importance for the supply of digitalized voice quality, is isolated as the most crucial to the determination of a subscriber's terminal reservation price as well as the subscriber's usage demand. The text is supplemented by eight figures and an appendix presents representative power budgets for a global beam mobile satellite link. (33 references) (Author/EW)

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The Mobile Satellite Services Market

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Sixteenth Annual Telecommunications Policy Research Conference

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THE MOBILE SATELLITE SERVICES MARKET

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Mobile satellite (MSAT) technology is the basis for a new component of the telecommunications industry capable of providing services to small inexpensive subscriber terminals located almost anyplace in the world. The market for MSAT space segment capacity (bandwidth and power) is a natural monopoly that can be logically and technically distinguished from the market for MSAT services. The production of services relies on satellite power and bandwidth as factor inputs. From a social welfare perspective it is advantageous that the market for services be competitive to generate incentives for firms to probe the cost and demand surfaces of the service space. The demand for services is defined by subscriber choices in two distinct markets. The initial choice involves the selection of a terminal, determined by a tradeoff between price, functionality, and the price of usage, which may vary for terminal types. The subscriber then chooses among service offerings subject to the constraints imposed by the technical attributes of the terminal. The "physical layer" service standards, which specify terminal antenna gain, modulation, and error-correction coding, are evaluated in an engineering-economic analysis that models the variable cost of producing basic communications capacity. The demand for MSAT services is considered in two parts: a reservation price for the subscriber terminal and the demand for usage. The demand for usage is a function of a vector of quality attribute variables. Of these, channel throughput (measured in bits per second), because of its importance for the supply of digitized voice quality, is isolated as most crucial to the determination of a subscriber's terminal reservation price as well as the subscriber's usage demand.

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Introduction: Mobile Satellite Technology

Mobile satellite (MSAT) technology provides a means of communicating over long distances using small transportable satellite terminals. It is a by-product of recent technological advances achieved in the telecommunications, integrated circuit, and aerospace industries. The commercial success of MSAT technology depends on the ability of electronics firms to manufacture small, inexpensive satellite terminals and of aerospace firms to develop the requisite functionally sophisticated satellites. Its promise is to allow users to communicate from virtually anywhere—the open highway, the middle of an ocean, a campground—to the rest of the world via an interconnection with the public telephone network functionally equivalent to (and probably more versatile than) that available with a common telephone circuit.

An MSAT system may be viewed as a mobile radio system unencumbered by distance constraints. A single geostationary satellite can provide coverage to over one third of the earth's surface, whereas the coverage of a cellular or mobile radio system is typically restricted to urban areas. Early advocates envisioned an integrated MSAT and land-based cellular radio system providing a continuity of mobile communications coverage across the entire continent of North America.[1]

Another view might be to consider MSAT technology as the most pronounced example of the trend in the satellite industry toward networks of ever-smaller user terminals for specialized applications. A like example is the Very Small Aperture Terminal (VSAT) satellite technology [2] that has recently emerged as a means for clients to implement private data networks that bypass the public switched network. VSAT systems employ fixed terminals that are generally larger than MSAT terminals, and they utilize a different frequency band. But VSAT and MSAT systems are comparable in their network design, consisting of numerous distributed subscriber terminals. Conventional satellite systems, in contrast, rely on large centralized earth stations to provide high-capacity long-haul links between nodes in long distance telephone networks. The importance of small-terminal networks for the future of the satellite industry is notable in the face of the challenge of fiber optic cables in the long-haul point-to-point telecommunications market.

The technological capability for mobile satellite communications has existed for at least twenty years, but until recently has been viewed as unready for commercial applications. The remarkable progress in the field of integrated circuit technology — increasing computing power and declining costs of microprocessors — has combined with similar progress in the field of microwave electronics to enable the mass production of sophisticated signal processing systems for capable yet inexpensive subscriber terminals.

Mobile Satellite Services

A mobile satellite system consists of two distinguishable components: the space segment — including fixed earth station and satellite — and the population of mobile terminals. It is the space segment that provides the medium for communication — the bandwidth and radiated power required for transmissions of electromagnetic signals to carry the necessary distances between the fixed earth station and remote terminals. "Bent pipe" remains an apt metaphor for the MSAT space segment that is considered in this study. The signal transmitted in the direction of the satellite is returned to earth essentially unchanged but for amplification and a translation in frequency.

The functionality that underlies the provision of MSAT services involves much more than the provision of space segment capacity. A service, as defined here, also includes the technology necessary to format, encode, and modulate the signal, and to provide dynamic access to a portion of the available space segment capacity in coordination with other users. The range of possible service technologies is large, and there exists little universal agreement as to the "best" technologies. In reality, the notion of "best" has no general meaning for MSAT service technologies because of the diverse requirements, economic status, and preferences of the diverse populations of subscribers which will ultimately generate the demand for MSAT services.

An alternative to the bent-pipe model of space segment capacity has emerged with research and development in on-board satellite processing technologies.[3] While on-board processing satellite technology has excited interest in the satellite industry, it is questionable whether its technical merits will soon provide sufficient economic benefits to offset its risk. For one thing, on-board processing centralizes the choice of service technologies. The analysis contained in this paper demonstrates just a few of the reasons why such a centralized choice of service

technologies is difficult to make, and why, in the worst case, it may lead to substantial welfare losses.

The distinction between MSAT and other satellite services has been made a formal part of the international and domestic allocation and management of radio spectrum. A valued, and as yet largely unused, portion of L-band spectrum has been reserved specifically for MSAT services.[4] What then is meant by an MSAT service? First, the term "mobile" in the categorization "mobile satellite service" is taken here to be a historically generated imprecision that should be clarified. MSAT technology is distinguished from other satellite technologies by the small size, or more specifically, the low EIRP (effective isotropic radiated power) of the subscriber terminal. Large satellite earth stations secured to moving platforms fall outside of this definition, while lunch box-sized terminals affixed to the roof of a building might be included. Standard INMARSAT (International Maritime Satellite Organization)[5] terminals equipped with their one-meter antennas definitely constitute the upper bound on size.

As a general definition: A communication service is the set of functional processes that convert digitally encoded intelligence to an electrical signal, encoded in time and frequency, compatible with a system to interchange information between nodes of a communications network. The MSAT service is merely one link in an extended telecommunication system involving compatible interconnections between subnetworks of terrestrial and possibly even other satellite channels. An MSAT service enables a subscriber equipped with an MSAT terminal and proper authorization to log on (achieve a connection) with the fixed earth station computer, to be assigned a channel, and to carry on communications with the earth station. The fixed earth station, in turn, provides a compatible interface to public or private switched networks.

Since the bandwidth and radiated power provided by the space segment are the physical medium necessary for the production of communications capacity, they are considered economic inputs to the production of MSAT services. An analogy with the transportation industry may be ventured: A highway system represents transportation capacity; transportation services, however, are the highly specialized revenue-producing private uses of the highways — trucking, bus lines, taxi cabs, etc. By analogy, the MSAT space segment is the roadway; and MSAT services the means and terms of information conveyance.

Service Standards Model

The design of an efficient MSAT service communication channel is a fairly complex affair. First the information must be organized in a consistent fashion with starts, stops, fillers, and transformations (*framing*). Next, it is encoded to increase the probability of its successful reception (*error-correction coding*). The RF carrier is modulated with rapid changes in phase and frequency which encode the information in an electromagnetic formula (*modulation*). The actual information must be preceded by intervals of standardized synchronization patterns to allow the necessary coordination between transmitter and receiver (*burst formatting*). The data is transmitted over the satellite channel, but only at coordinated times and frequencies to avoid interference with other transmitters (*channel access*). Finally, for a given application it may be necessary to determine whether transmission errors have occurred. If so, a repeat request message must be transmitted on the return channel to inform the sender to repeat the transmission. If the received message is error free, the receiver must still transmit an acknowledgment to the sender (*error detection and Automatic Repeat reQuest* (ARQ)). In addition to all of the above requirements, the data messages must be appended with an additional assortment of address, routing, sequence, and service description information so that it may be passed from the MSAT network through the necessary sequence of terrestrial networks to its destination in a compatible fashion (*the network protocol.*).

Technologies for all of these processes have been developed and standardized for other types of networks and communication media. These technologies may or may not be suitable in the MSAT environment. If standardized technologies can be culled from other types of communication systems and applied to the MSAT system without degradation of performance, there are economic benefits for doing so. The avoidance of development costs is probably the most compelling. Interoperability and the interchangeability of components and algorithms are also important incentives for the adaptation of existing standards. The seven-layer International Standards Organization's Reference Model for Open Systems Interconnection (OSI)[6] provides an explicit conceptual device as a guide for such evaluations. As a general rule, the technologies of the three lowest layers of the OSI model (the physical, data link, and network layers), which encompass the processes listed in the preceding paragraph, cannot be readily generalized across diverse communications systems.

The standards of the physical layer , the lowest of the seven layers, which involve specification of hardware, and modulation and error-correction coding techniques, typically require the most

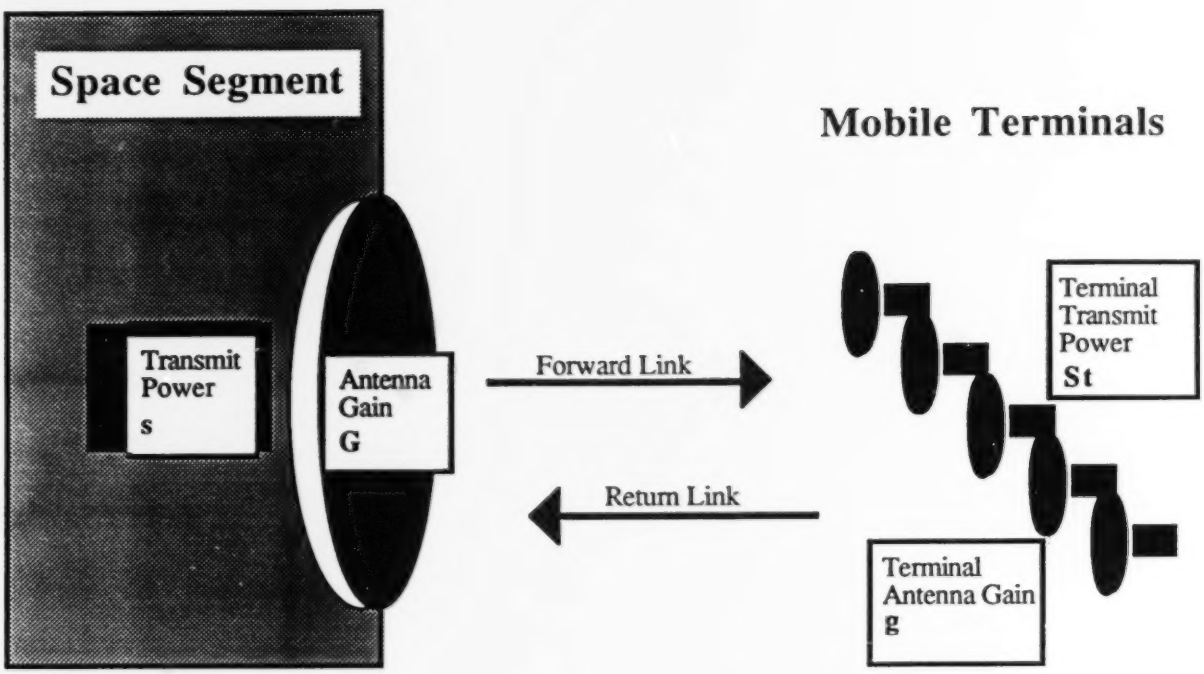
specialized engineering attention due to the impossibility of standardizing communication media. They therefore form the focus for the analysis of MSAT service technologies in this paper. Whereas higher level user features might be considered in a more extended analysis of MSAT service technologies, such features are related to specific applications of the MSAT communications capability, and do not have as direct a relationship to the MSAT-specific technologies as do the physical layer standards.

Service Capacity Production Model

Although the range of technologies that make the production of MSAT services possible is large and varied, and isolated examples could warrant extensive individual analytical treatments, a much streamlined model of MSAT service production is introduced here that restricts the boundaries of the analysis to include only those variables with overt significance in the economics of service production. The system for MSAT service production consists of the space segment, which contributes bandwidth, forward link satellite transmit power, and satellite antenna gain to the production equation, and the population of terminals, which contribute terminal antenna gain and return link transmit power. Figure 1 provides a representation of this production system. The forward link refers to the communications path from the fixed earth station through the satellite to all the mobile terminals in the system. Communications traffic in the opposite direction, from the terminals to the earth station, travel over the return link.

It may be noted that the production system includes only the portions of the forward and return links between the satellite and the mobile terminals. Of course satellite resources must also be dedicated to complete the links between the satellite and fixed earth station. However, since the earth station may be equipped with an antenna having a gain 10^4 times greater than the gain of mobile terminal antennas, the combination of satellite power and antenna gain required for this half of the satellite link is something in the range of 4 orders of magnitude lower than that required to reach the mobile terminals. Therefore, the economic variables associated with the earth station-to-satellite links are not considered explicitly in the production model. Their economic impact is assessed merely as a contribution to the substantial fixed costs of deploying the space segment, costs which would also include satellite launch costs, earth station construction, and so forth.

In a short-run evaluation, virtually all space segment costs are fixed costs since once capacity is



Satellite Effective Isotropic Radiated Power: **E = sG**

Figure 1. Bounded Mobile Satellite Service Capacity Production Model

deployed the marginal cost of its usage is insignificant. A long-run evaluation, however, properly treats the level of production of space segment factors as variables.

MSAT Industry and Services Market Model

The general industry model adopted here portrays the MSAT space segment provider as a carrier's carrier. The products of the space segment provider — satellite EIRP (effective isotropic radiated power, the product of transmit power and antenna gain), antenna gain, and bandwidth — are marketed to independent service-providing firms as inputs to the production of MSAT services. The producer of the MSAT space segment factors constructs the earth stations and develops, launches , and operates the satellites. It also may opt (if permitted) to retain some capacity for its own production and sale of MSAT services. Since the space segment provider might be disposed to refuse the sale of capacity to other firms or otherwise engage in discriminatory practices to frustrate competition with its own service offerings, it is assumed that a policy option is exercised to enforce the segregation of the capacity and services markets through regulation. Furthermore, it is assumed that subscribers to MSAT services are obliged to purchase their MSAT terminals from independent suppliers.

Figure 2.A-B is a schematic representation of the industry that shows its component markets — the space segment, service, and terminal markets. The government regulator in this industry representation is shown to exert a possible influence over three control variables related to (1) spectrum allocation and management, (2) space segment price regulation, and (3) service and technology standardization. Through a previous but related analysis it was concluded that the MSAT space segment market exhibits characteristics of a natural monopoly.[7] As such, it may require regulatory intervention to ensure an efficient and fair economic development of its allocated spectrum. The regulatory segregation of the space segment and services markets would, in principle, foster competition in the services market and, hopefully, facilitate the efficient introduction and assimilation of innovative service offerings and technologies. With open access to space segment factors, prospective service providers should not encounter overwhelming entry and exit costs. The competitive markets for services and terminals obviates the need for regulatory oversight since consumers should presumably have access to a range of service choices.[8] Whether government intervention in development and management of service standards is warranted is an open question. The organization of the industry as depicted in Figure 2 is not meant to be prescriptive, but rather is intended to provide some definition and context for the MSAT services market necessary for

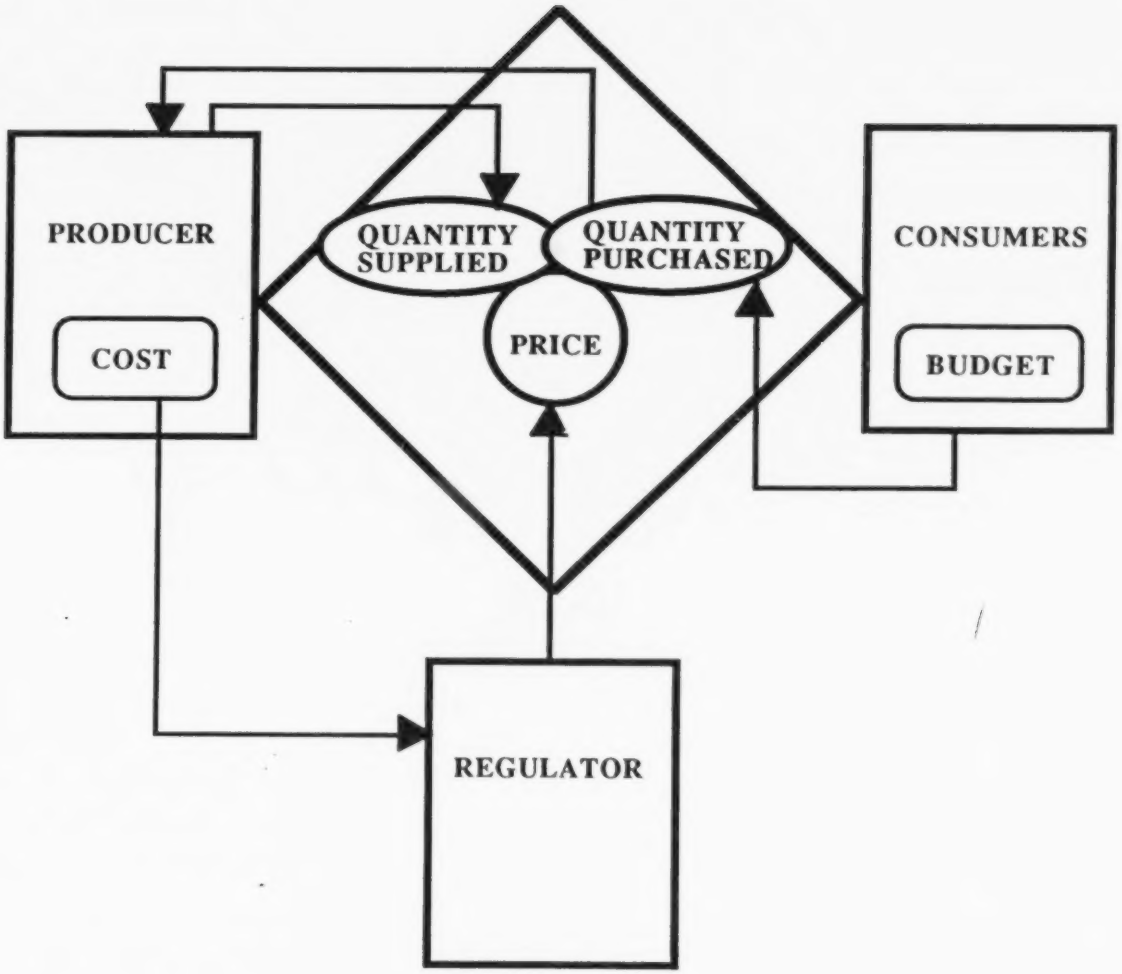


Figure 2.A Diagramatic Representation of a Regulated Natural Monopoly Market

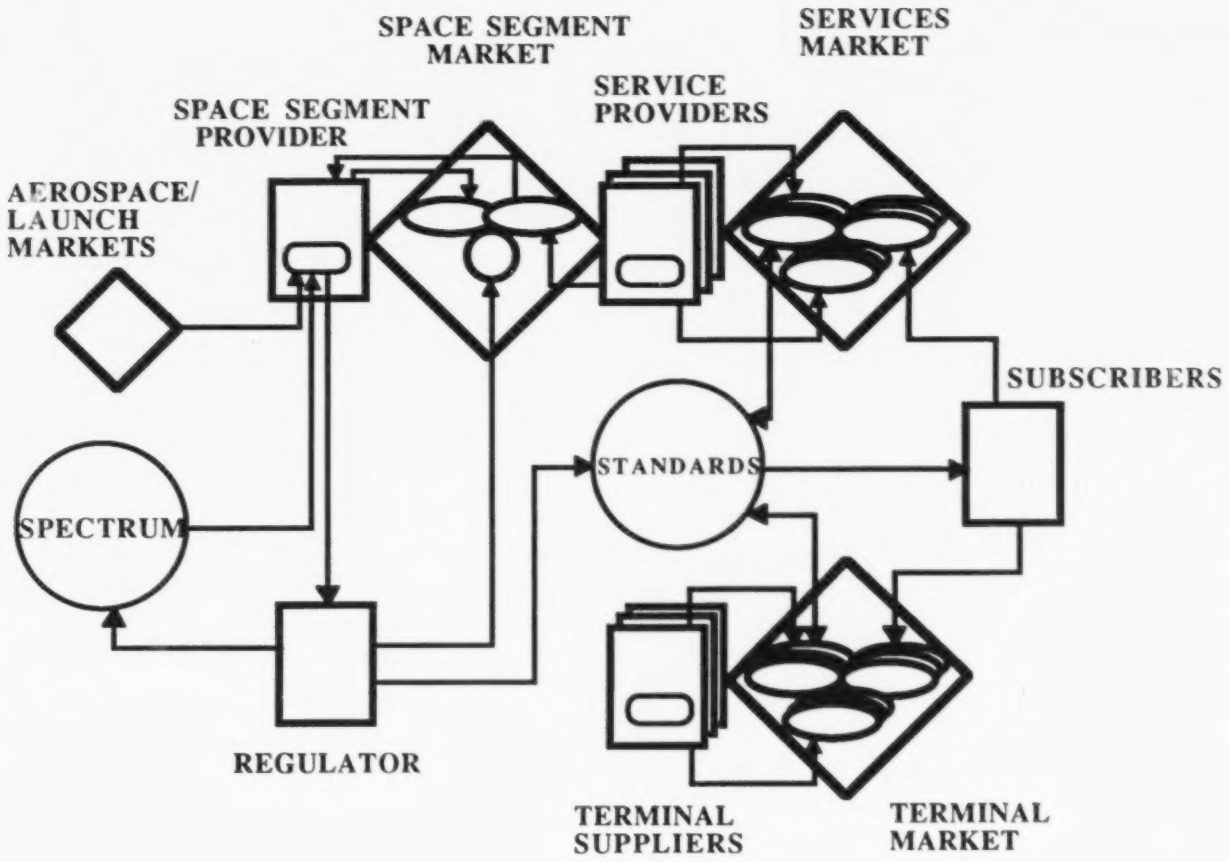


Figure 2.B Diagramatic Representation of the Mobile Satellite Industry

this paper's analysis of the market's supply and demand characteristics.

A service providing firm must make the choices of technologies that it will use to produce the services it intends to offer for subscription. The service provider will have access to the space segment infrastructure of RF transmission and receiving hardware located at the fixed earth station site, but will supply its own signal processing and network control hardware. If the satellite has a linear transponder, the satellite transmit power of a given forward link signal will bear a linear relationship to the uplink signal power. Thus the forward link satellite transmit power allocated to a specific service provider's signal may be controlled from the earth station, and the satellite power resource can, in principle, be priced accordingly. Since the signal transmitted by the satellite is simply an amplified and translated replica of the signal received on the uplink, the bandwidth of the signal transmitted through the satellite is also determined from the fixed earth station, and a bandwidth price can therefore also be assigned.

Service Capacity Production

Viewed from the perspective of a service-providing firm, the cost of MSAT communication capacity production may be separated into two parts. First, there are the fixed costs associated with the signal processing and network control hardware that it develops and implements. These costs will be a function of the complexity of the technology. It is necessary, of course, that the mobile terminals subscribing to the service operate with compatible technology. Second, there will be the variable costs associated with the amounts of satellite power and bandwidth used to provide the service. The variable costs will be considered here.

Communications capacity is a function of received signal power and bandwidth. Shannon's elegant capacity theorem[9] is familiar to individuals working in many diverse engineering and scientific fields and is stated below.

$$Q = B \log_2\left(1 + \frac{S}{BN_o}\right) \qquad (1)$$

Q represents communications capacity in units of bits per second (bps), B represents bandwidth, S received signal power, and N_o noise density. It is actually the theoretical limit for errorless communications capacity for constrained signal power and bandwidth.

Modern communications technologies exhibit the same power-bandwidth tradeoff for less-than perfect error rates. We examine one of the most promising of these technologies for application in the mobile satellite environment. It involves quadrature phase-shift keyed (QPSK) modulation, punctured constraint length-7, 1/2-rate convolutional error-correction coding, and Viterbi decoding.[10] It is impossible to justify the selection entirely within a spare few paragraphs in light of the awesome number of alternatives. From the perspective of an economic analysis, however, the specific choice of technologies is not the relevant issue; it is the power-bandwidth transformation that is of interest. In another previous analysis, an approximate capacity function of power and bandwidth analogous to equation (1) was derived for this specific set of modulation and error-correction coding techniques.[11]

$$Q(S, B, N_o, \alpha(P_b)) = 2B\left(1 - \exp\left[-\frac{S}{2\alpha(P_b)BN_o}\right]\right) \qquad (2)$$

An additional variable, $\alpha(P_b)$, is introduced which is a function of the target bit error probability. ($\alpha(P_b = 10^{-5}) = 1.55$ and $\alpha(P_b = 10^{-3}) = 1.18$.)

Figure 3 plots equation (2) as an isoquant (Q=1, $P_b = 10^{-5}$) in a plane having dimensions of power and bandwidth together with experimental performance data points to indicate the adequacy of the approximation. Also shown in the figure are Shannon's theoretical limit for errorless communication and an isoquant for Trellis Coded Modulation (TCM), another technology in the forefront of communications field.[12] Because of phase irregularities in typical MSAT channels, it might not ever be possible to fully exploit the performance of TCM for MSAT applications.[13] However, it is included to provide some sense of the innovation frontier in MSAT communication technologies. It indicates that another dimension might be included to the production factor space and labeled "technological complexity"; every improvement in efficiency comes at a cost in complexity. Research and development in TCM techniques is being actively pursued by terrestrial microwave system designers. Terrestrial power is cheap compared to space power; furthermore, spectrum in the terrestrial microwave band is very valuable.[14]

Forward link received power is modeled as a function of space segment inputs:

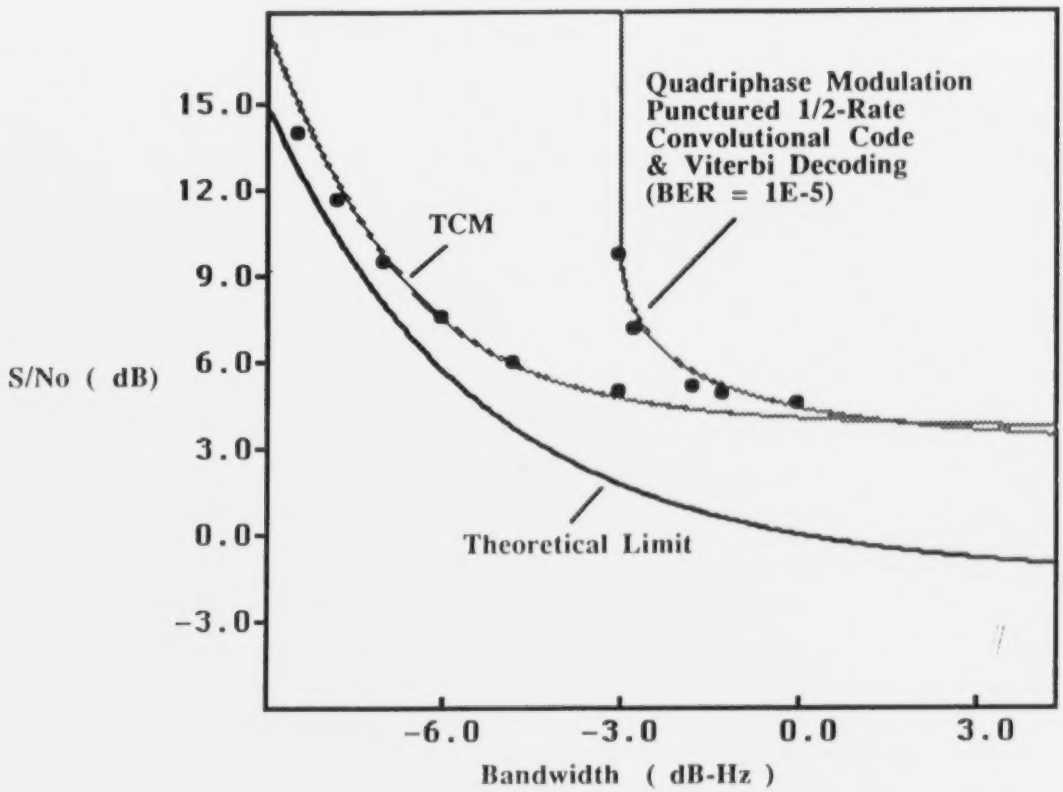


Figure 3. Service Capacity Production Isoquants — Q = 1 bps

$$\frac{S}{N_o} = sg_s dg = Eg \tag{3}$$

where s denotes satellite transmit power, g_s, satellite antenna gain, g terminal antenna gain, and d is a constant accounting for all other link parameters that are relatively invariant.[15] The product $E = sg_s d$ may be regarded as the space segment factor input that is purchased in combination with bandwidth, B, for the production of forward link capacity. The service provider will be confronted with factor prices for these inputs, denoted as P_E and P_B, and must solve the problem of further specifying the choice of technologies by selecting the point on the capacity isoquant whereon to standardize. Specifically, the problem is to:

$$\text{Minimize:} \qquad C(E, B) = EP_E + BP_B$$

$$\text{Subject to:} \qquad Q = 2B\left(1 - \exp\left[-\frac{Eg}{2\alpha B}\right]\right) \tag{4}$$

The first order conditions are:

$$P_E = \lambda \frac{g}{\alpha} \exp\left(-\frac{Eg}{2\alpha B}\right)$$

$$P_B = \lambda 2\left[1 - \exp\left(-\frac{Eg}{2\alpha B}\right) - \frac{Eg}{2\alpha B}\exp\left(-\frac{Eg}{2\alpha B}\right)\right] \tag{5}$$

Substituting for the Lagrangian multiplier obtains:

$$\frac{P_B}{P_E} = \frac{2\alpha}{g}\left[\exp\left(\frac{Eg}{2\alpha B}\right) - 1 - \frac{Eg}{2\alpha B}\right] \tag{6}$$

The equality constraint is applied and the following substitutions made:

$$\ln\left(1 - \frac{Q}{2B}\right) = \frac{Eg}{2\alpha B} \; ; \text{ and } \; \frac{\frac{Q}{2B}}{1 - \frac{Q}{2B}} = \exp\left(\frac{Eg}{2\alpha B}\right) - 1$$

$$\frac{P_B}{P_E} = \frac{2\alpha}{g}\left[\frac{\frac{Q}{2B}}{1 - \frac{Q}{2B}} + \ln\left(1 - \frac{Q}{2B}\right)\right] \tag{7}$$

At this point it is necessary to make an approximation, which consists of retaining only the first term in the Taylor expansion of the natural logarithm.[16]

$$\frac{P_B}{P_E} = \frac{2\alpha}{g}\frac{\left(\frac{Q}{2B}\right)^2}{\left(1 - \frac{Q}{2B}\right)} \tag{8}$$

B is then solved for to obtain the optimal quantity of bandwidth to produce a capacity of Q bps.

$$B = \frac{Q}{4}\left(1 + \sqrt{1 + \frac{8\alpha P_E}{gP_B}}\right) \tag{9}$$

Thus, if factor input prices for E and B, the subscriber terminal antenna gain, g, and the service error rate factor, α, are known, the optimal bandwidth per bps of capacity can be obtained.

$$B_T = \frac{1}{4}\left(1 + \sqrt{1 + \frac{8\alpha P_E}{gP_B}}\right) \tag{10}$$

The comparable expression for the satellite power input E is derived from this value as follows:

$$E_T = -2B_T \ln\left(1 - \frac{1}{2B_T}\right) \tag{11}$$

These values specify a vector in the factor space which characterizes the relative levels of the

two factors required to produce capacity for a specific service technology. Once the technology is specified to this level, only the ratio of inputs characterized by this vector, to be referred to as the coding rate vector (E_T, B_T), will suffice for capacity production. Figure 4 superimposes production isoquants, which correspond to three different coding rate vectors (E_i, B_i), on the production isoquant previously displayed in Figure 3.

For a given coding rate vector, the production function for forward link communications capacity takes on the Leontief form:[17]

$$Q_F = \min\left[\frac{Eg}{\alpha E_T}, \frac{B}{B_T}\right] \tag{12}$$

We begin here to make a distinction between *total* forward link capacity, Q_F, and return link capacity *per channel*, Q_R. A return link capacity per channel function analogous to equation (12) can be produced by a symmetrical argument. The signal-power-to-noise-density ratio received at the satellite on a return link communication channel from a mobile terminal is:

$$\frac{S}{N_o} = g_s d_R g s_t = G g s_t \tag{13}$$

where d_R is the return link equivalent of the constant d introduced in equation (3);[18] g_s is the satellite antenna gain, g the terminal antenna gain, and s_t the terminal transmit power. The main difference between equations (3) and (13), which apply to the forward and return links respectively, is the replacement of the satellite transmit power in the former with the terminal transmit power in the latter. That is, transmit power on the return link is produced by the subscriber rather than the space segment. If the magnitude of bandwidth expansion for error-correction coding is set by B_T, the return link capacity per channel function becomes:

$$Q_R = \min\left[\frac{G g s_t}{G_T \alpha}, \frac{B}{B_T}\right] \tag{14}$$

Once the space segment is deployed, the variable G is fixed and is available in the same quantity to all service providers and subscribers. Thus while it is reasonable to assign a price

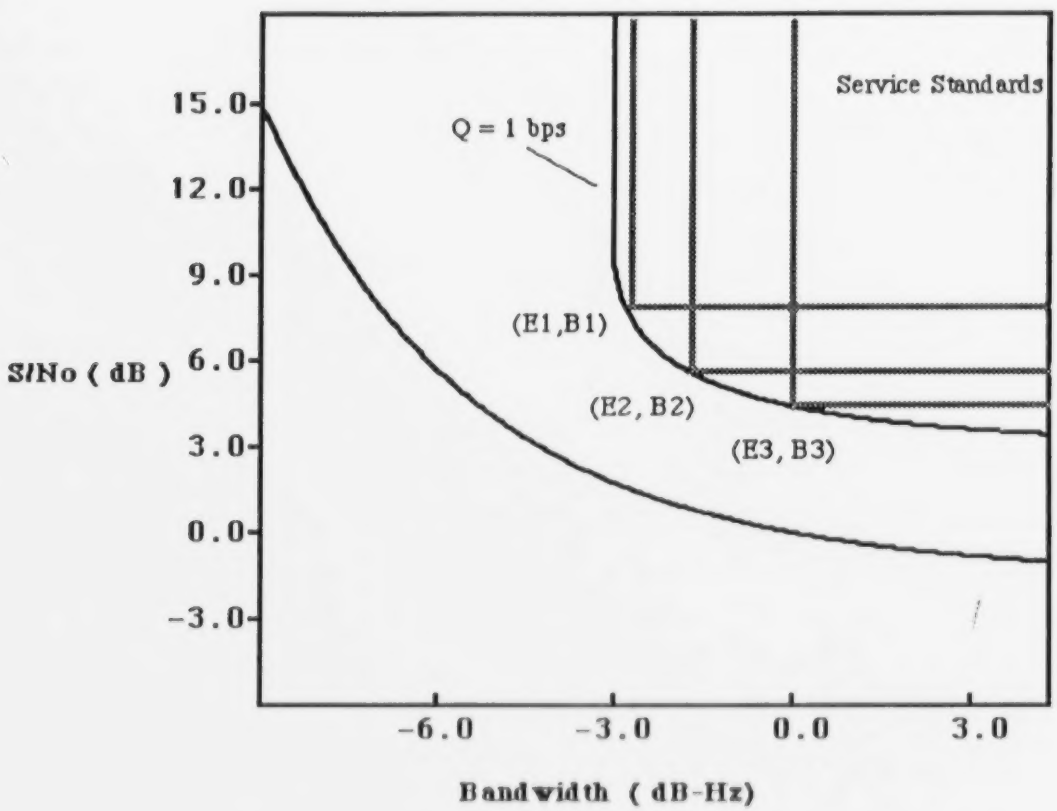


Figure 4. Leontief-Form Service Capacity Production Functions for Specified Modulation and Error-Correction Coding Standards

to the forward link satellite transmit power variable, E, and forward and return link bandwidth, B, a price for G would have no similar meaning.

The import of this observation is revealed in the form the cost functions for forward and return link capacity take on. Space segment cost as a function of forward link capacity is:[19]

$$C(Q_F) = Q_F\left(\frac{\alpha E_T P_E}{g} + B_T P_{BF}\right) \tag{15}$$

while space segment cost as a function of return link capacity is:

$$C(Q_R) = Q_R B_T P_{BR} \tag{16}$$

A distinction is made between forward and return link spectrum prices because they can and probably should differ. The difference would not result from differing incremental costs of production but from differing demands.

Space Segment Prices

Discrete increases in available MSAT spectrum can be achieved through the deployment of additional spot beams in the satellite spot beam antenna array. As long as two beams are separated sufficiently to prevent interbeam interference the same allocated spectrum can be used for transmissions over both beams. Therefore, the produced space segment spectrum, B_S, is a function of three variables:

$$B_S = \frac{B_A n}{r} \tag{17}$$

B_A is allocated spectrum (assume that equivalent amounts of spectrum are allocated for forward and return link development), n the number of spot beams in the satellite antenna array, and r the number of distinct frequency assignments.[20] For a fixed area of regional coverage, the antenna gain per spot beam increases as the number of spot beams increases. Thus the production of the space segment variable corresponding to transmit power, E, is influenced (favorably) by the introduction of additional spot beams. The satellite antenna gain is a linear function of the number of spot beams:

$$g_s = \frac{nfg_e}{A} \tag{18}$$

where g_e is the gain of a global beam antenna (approximately 20 dB at beam center), f a factor to account for beam overlap, and A is a variable equal to the regional area covered by the spot beam array divided by the total area of a global beam coverage. Substituting this expression in equation (3) results in:

$$\frac{S}{N_o} = \frac{sng_e fdg}{A} = \frac{sneg}{A} = Eg \tag{19}$$

The constants g_e, f, and d are condensed into a more comprehensive constant e. Combining equations (17) and (19) we solve for satellite design variables s and n.

$$n = \frac{rB_S}{B_A}; \qquad s = \frac{EAB_A}{reB_S} \tag{20}$$

The space segment costs for producing E and B can be stated as a function of the incremental costs of satellite power and antenna spot beams:[21]

$$C(E, B_S) = C_f + \frac{EAB_A}{reB_S} C_s + \frac{rB_S}{B_A} C_n \tag{21}$$

where C_f represents fixed space segment costs, and C_s and C_n are the incremental costs of satellite transmit power and antenna spot beams. Now the factor prices for space segment power and bandwidth can be related to the marginal costs of their production. That is, it is assumed that service-providing firms will face space segment factor prices of the form:

$$P_E = \Gamma \frac{\partial C(E,B)}{\partial E} = \Gamma \frac{AB_A}{reB_S} C_s = \Gamma \frac{CS}{E}$$

$$P_B = \Gamma \frac{\partial C(E,B)}{\partial B_S} = \Gamma \left(\frac{r}{B_A} C_n - \frac{EAB_A}{reB_S^2} C_s \right) = \Gamma \frac{1}{B_S} (CA - CS) \qquad (22)$$

where CS and CA are the total costs of the satellite's transmit power and antenna subsystems, and Γ is a constant which must be sufficiently greater than one to allow the space segment provider to recover fixed costs.[22]

It is apparent from equations (22) that the space segment factor prices are dependent on situation-specific variables such as the quantity of allocated spectrum and the regional area to be covered. For a sufficiently large bandwidth of allocated spectrum, the factor price for spectrum will be close to zero.

Forward link bandwidth is produced jointly with return link bandwidth. Consequently, a unique incremental cost cannot be attributed to either quantity. Rather, an efficient equilibrium should ensure that the combined prices ($P_{BF} + P_{BR}$) cover the joint incremental costs of MSAT bandwidth production. The relative levels of demand for forward and return link bandwidth should determine actual prices.[23]

The MSAT Service Space

We now move from the perspective of a service provider designing a system for the production of raw communications capacity to the perspective of a designer of services. The service provider strives to satisfy the preferences of subscribers; hence, the the service provider must assume the perspective of a subscriber and attempt to model his preferences.

The MSAT service space may take on an arbitrarily large number of dimensions. Differentiation between services may be made on the basis of mobile categories (e.g. land, maritime, aeronautical), types of terminals, service description, and quality features such as capacity per channel, message delay, reliability, and so forth. If it were necessary to reduce the

entire scope of potential communication services to a basic set, it is generally acknowledged that such a set would include three fundamental categories of services.[24]

1. Voice communications,
2. Interactive data communications, and
3. File data communications.

The nature of voice communications is apparent. Interactive data communications involve short bursts of data followed by relatively long quiescent intervals. File data communications involve the transfer of large blocks of information. These basic service categories place divergent requirements upon a data network.

Since the service space may have a large and at the outset unknown number of dimensions, it is conceptually useful to consider the service space as mapping into a more limited but better generalized quality attribute space. The basic quality attribute dimensions that describe digital communication services are:

1. Throughput or capacity per channel,
2. Bit error rate,
3. Message error rate,
4. Message delay,
5. Connection delay, and
6. Blocking probability.

The MSAT subscriber will select services and, indirectly, quality attributes for subscription and utilize them at levels that maximizes the net of benefit and cost. We assume that the subscriber's utility function is quasi-linear and that the utility derived from MSAT services is additively separable,[25] i.e.

$$U(m, \mathbf{x}, \mathbf{q}, \mathbf{Z}) = U(\mathbf{x}) + U(\mathbf{q}, \mathbf{Z}) + m$$

where $\mathbf{x}$ is the vector of all other goods consumed, $\mathbf{q}$ the vector of quantities of MSAT services used, $\mathbf{Z}$ the matrix of quality attribute variables associated with the vector of services, and m a numeraire quantity corresponding to money and having a price of 1. Then, restricted only by

the finite number of standards that span the MSAT service space, the subscriber will select and utilize services at quality levels in accordance with the first order maximization conditions:[26]

$$\frac{\partial U}{\partial q_j} = \frac{\partial P(q_j, \mathbf{Z}_j)}{\partial q_j} \quad ; \quad \frac{\partial U}{\partial Z_{jk}} = \frac{\partial P(q_j, \mathbf{Z}_j)}{\partial Z_{jk}} \tag{23}$$

where $P(q_j, \mathbf{Z}_j)$ is the price of a quantity q_j of the service j as a function of the vector of quality attribute variables. Note that $\partial U/\partial m = 1$, due to the quasi-linear assumption.

The production costs (from which hedonic price functions can be inferred) of the quality attribute variables throughput and bit error rate are contained explicitly in the models developed previously. Production of the remaining quality variables, however, is a function of the technologies used to implement the data link and network layers of the OSI model, just outside the scope of the physical layer production models discussed in this paper. Message error rate, for example, is controlled through ARQ schemes imbedded in the data link and network protocols. Delay and blockage variables are essentially a function of the ratio of realized to potential capacity. The results of queuing theory show that the delay performance of a system undergoes marginal improvements with reductions in the ratio of offered load to available capacity, and can therefore be improved with the purchase of additional reserve capacity. Thus, basic communications capacity is the common input to the production of specified delay and blockage parameters.[27]

The Digital Voice Service

It is expected that the largest segment of MSAT subscriber demand will be that for voice services. Because of this, a good first-order characterization of MSAT service economics can be obtained through an analysis restricted to a consideration of voice services.

The utility derived by a subscriber from usage of a voice service is essentially a function of the quantity of usage and the channel throughput.[28] The quantity of voice service usage is measured in units of time, τ. Channel throughput, ζ, determines the quality of the voice channel, the bit rate available for processing by the voice digitization algorithm. A higher bit rate, since it allows a higher sampling rate with greater resolution, allows the voice waveform

to be encoded with greater accuracy and correspondingly better quality. In the interest of tractability we will assume that the subscriber's utility function for usage of a voice service is multiplicatively separable, such that:

$$U(\tau, \zeta) = U(\tau) \cdot U(\zeta) \tag{24}$$

Voice Usage Demand

A utility function for usage based on a constant price elasticity of demand is proposed.

$$U(\tau) = \frac{\varepsilon}{1+\varepsilon} \tau_o \left(\frac{\tau}{\tau_o}\right)^{\frac{1+\varepsilon}{\varepsilon}} \tag{25}$$

where ε is the subscriber's price elasticity of demand for usage, and τ_o is a constant. The inverse demand function for usage can be obtained from equation (25) by differentiating $U(\tau,\zeta)$ with respect to τ as follows:

$$\frac{\partial U(\tau,\zeta)}{\partial \tau} = U(\zeta) \frac{\partial U(\tau)}{\partial \tau} = U(\zeta) \left(\frac{\tau}{\tau_o}\right)^{\frac{1}{\varepsilon}} = P(\tau, \zeta) \tag{26}$$

As the shapes of the demand curves shown in Figure 5 demonstrate (the parameters for the demand curves are: $\varepsilon_1 = -1.5$, $\tau_1 = 500{,}000$; $\varepsilon_2 = -2.0$, $\tau_2 = 3000$; and $\varepsilon_3 = -3.0$, $\tau_3 = 360$), the communications conducted by a typical MSAT subscriber are not all of equal value. As the usage price approaches zero, MSAT services become a substitute for conventional long distance telecommunication services, resulting in large quantities of usage per average subscriber.

The Demand for Voice Service Quality

The utility of channel throughput as perceived by a subscriber influences the willingness-to-pay for the voice service. The utility is not really a direct function of throughput, but rather an indirect function that depends on the performance of the digitized voice encoders and decoders

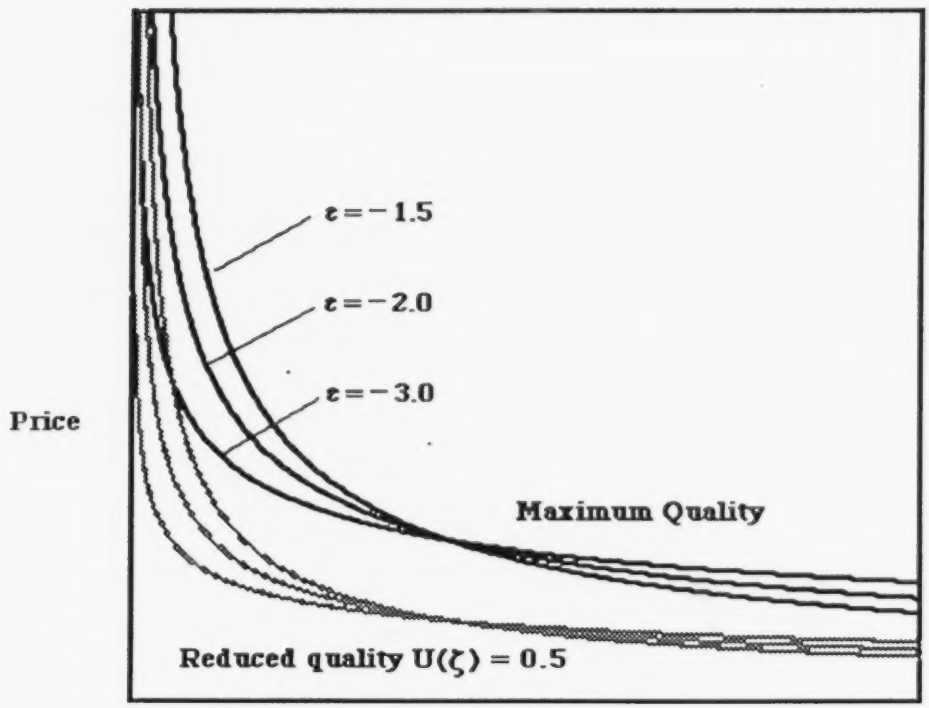


Figure 5. Demand Functions for MSAT Voice Service Usage

(vocoders). The benchmark assumed for the subjective evaluation of digitized voice quality is the standard 4 kHz telephone circuit that everyone is familiar with. A digitized MSAT voice channel of a subjective quality equal to this benchmark would merit a utility rating of 1.

A substantial amount of research and development has gone into decreasing the digital channel throughput required to maintain an acceptable voice quality. Public telephone networks typically use Pulse Coded Modulation (PCM), which requires a throughput of 64 kbps (thousand bits per second), to transmit voice signals. Such a large throughput is not practical for an MSAT channel. With some degradation in quality, more complex forms of digital voice encoding may be deployed which require substantially less channel capacity. The coding options are numerous. For instance, based on a 5-point subjective assessment scale ("excellent", "good", "fair", "poor", and "unsatisfactory") that is used to compare vocoders, Adaptive Differential PCM (ADPCM) has achieved the "good" rating at 32 kbps, and Adaptive Predictive Coding (APC) has achieved the same "good" rating at 32 kbps and an impressive "fair" rating at 16 kbps. Linear Predictive Coding (LPC) techniques produce perfectly intelligible voice signals at channel throughput levels as low as 2.4 kbps, although with quality degradations as one might expect.[29]

The categorical subjective quality ratings referenced above are useful comparisons among technical alternatives but do not provide the information needed for proper economic comparisons. Intelligible speech with the diction of a robot will consistently elicit an unsatisfactory score in a subjective quality test because the listeners are not accustomed to it. For an assessment of utility, the critical measurement is how much less the subject would be willing to pay for a voice service of a specific substandard but intelligible quality. The utility function needed for this analysis should be a measure of the willingness-to-pay for quality, not a comparative ordering of subjective quality assessments.

Since the necessary data does not exist in the open literature, the following functional form is proposed to describe the utility of voice communications as a function of channel throughput.

$$U(\zeta) = 1 - \exp(-\beta\zeta) \qquad (27)$$

A large value of the parameter β will characterize the preferences of users who are more

indifferent to quality variations than users whose preferences are characterized by smaller β values. Figure 6 plots this functional form of utility as it varies with throughput for three values of β. ($\beta = 1x10^{-4}$, $2x10^{-4}$, and $4x10^{-4}$).

The Digital Voice Service Price

Having developed functional forms to characterize the benefits of the MSAT voice services, it is necessary now to return to a consideration of costs. Whereas the service-providing firm contracts for space segment capacity rights over some specified period, with prices for the space segment factors being set in accordance with the incremental costs of space segment bandwidth and power, the usage prices faced by the subscribers have to be established in a way which takes into account the dimension of time as well as the dimension of capacity measured as channel throughput. The subscriber actually purchases transmitted bits; i.e. the subscriber purchases a portion of space segment capacity for a specific interval of time— the product of capacity and time has the units of bits. Whether it is one second or an hour that is required for a given quantity of information to be transmitted, the amount of space segment capacity — and hence, in principle, the usage charge — should be the same (ignoring various channel management issues which provide for the reliable servicing of stochastic demand).

Consistent with these considerations, the price of MSAT telephone usage of duration τ will be:

$$C_u(\tau, \zeta) = \tau \zeta P_u \qquad (28)$$

where P_u is the usage price per bit of information communicated. P_u should bear a direct relationship to the incremental cost of service capacity obtainable from the cost functions given by equations (15) and (16).

The Subscriber Terminal

A complete representation of subscriber costs must include an analysis of the functionality and cost of the MSAT terminal, both of which have implications for the standardization and marketing of services. An important interrelationship between the markets for usage and terminals is that the forward link usage price is a function of the terminal antenna gain as

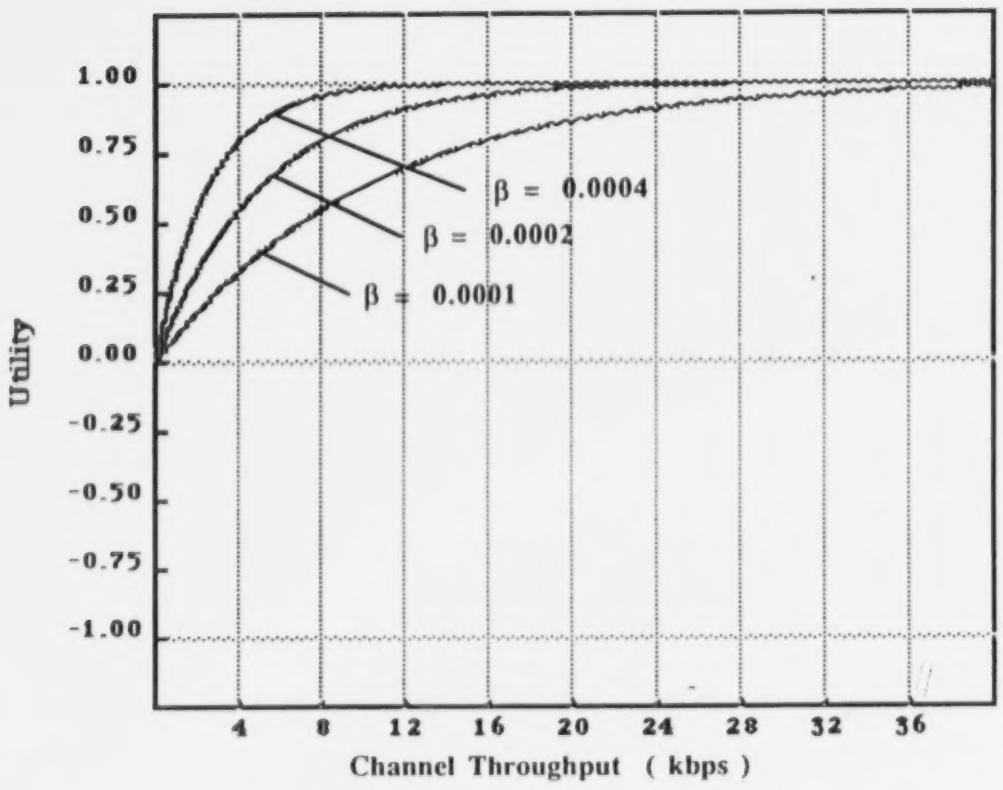


Figure 6. Suggested Utility Function for Digitized Voice Quality as a Function of Channel Throughput

indicated explicitly by equation (15). A second critical interrelationship is that the achievable return link throughput — hence, by equation (26), the demand for usage — is also a function of the terminal antenna gain.

Recall that the production function for return link capacity was given by equation (14). Since bandwidth is part of the return link usage price, and can be purchased in any quantity, the throughput of the return link is limited only by the product of the transmit power and antenna gain of the MSAT terminal.

$$\zeta_R = \frac{Ggs_t}{G_T\alpha} \tag{29}$$

The constraining variables in this function are the exceptionally low transmit power and antenna gain that are characteristic of MSAT terminals.

The three most important mobile terminal antenna gain classifications can be summarized as:

- g_l = 0 dBi = 1; low-gain non-steerable antenna;
- g_m = 12 dBi = 16; moderate-gain steerable antenna; and
- g_h = 22 dBi = 160; high-gain steerable antenna.

A high-gain MSAT terminal involves a one-meter dish antenna. At the other extreme, a low-gain antenna is small (about the size of a man's hand) and mechanically very simple.

Terminal Price

The price of the signal processing, user interface, and power amplifier components of an MSAT terminal should not exceed $3,000. Terminal prices in excess of this will be primarily a function of the terminal's antenna gain, since the higher the terminal antenna gain the more precise and sophisticated the steering mechanism must be. The market price for the high-gain terminals currently used with the INMARSAT system is approximately $25,000.[30] The prices for the other types of terminals have yet to be established, although a fair prediction of the price for a low-gain terminal is $3000.[31] It is more difficult at this time to estimate prices for the moderate-gain terminal, due to the uncertainty in the price of moderate-gain mobile antennas.

The lowest feasible price for a moderate-gain terminal appears to be approximately $5000 if produced in mass quantities, although the price could be as high as $8-10,000 if sales do not match expectations and scale economies cannot be fully realized.

The price of an MSAT terminal could be modeled as a function of both transmit power and antenna gain. However, the main determinate of price is the antenna gain. So for subsequent discussions, a terminal transmit power of 10 watts is assumed, and its cost is absorbed into the base terminal price. The MSAT terminal price will be modeled solely as an increasing function of antenna gain:[32]

$$P_t(g) = C_t g^{\gamma} \tag{30}$$

According to this formulation, if we let C_t = $3000, and $\gamma = 0.4$, the prices for low, moderate, and high-gain terminals are calculated to be about $3000, $9000, and $23,000 respectively, which captures in a sufficiently realistic way the dependency of terminal price on antenna gain.

Subscriber Terminal Reservation Price

For a prospective subscriber whose future demand for MSAT services is certain, the decision to purchase a terminal will be made when the total projected benefit is at least as large as the sum of the cumulative usage costs and the price of the terminal; i.e. when

$$U(\tau, \zeta) \geq C_u(\tau, \zeta) + P_t(g)$$

Stated another way: the consumer's surplus for usage must at least equal the terminal price for a prospective subscriber to enter the market. The consumer's surplus can be obtained as a function of P_u and ζ by first solving for τ in equation (26) and substituting the result in the expressions for $U(\tau,\zeta)$ and $C_u(\tau,\zeta)$, which are given by equations (25) and (28).

$$U(\tau,\zeta) - C_u(\tau,\zeta) = \frac{\varepsilon\tau_o}{1+\varepsilon}\left(\frac{\tau}{\tau_o}\right)^{\frac{1+\varepsilon}{\varepsilon}}\left(1 - \exp(-\beta\zeta)\right) - \tau\zeta P_u$$

$$= \frac{\varepsilon\tau_o}{1+\varepsilon}\frac{\left(\zeta P_u\right)^{1+\varepsilon}}{\left(1 - \exp(-\beta\zeta)\right)^{\varepsilon}} - \frac{\tau_o\left(\zeta P_u\right)^{1+\varepsilon}}{\left(1 - \exp(-\beta\zeta)\right)^{\varepsilon}}$$

$$= -\frac{\tau_o}{1+\varepsilon}\frac{\left(\zeta P_u\right)^{1+\varepsilon}}{\left(1 - \exp(-\beta\zeta)\right)^{\varepsilon}} \qquad (31)$$

This represents the consumer's surplus for usage or, alternatively, the subscriber's terminal reservation price. Eliminating the variable g in equations (29) and (30) allows the actual terminal price to also be formulated as a function of return link throughput:

$$P_t(\zeta_R) = C_t\left(\frac{\zeta_R G_T \alpha}{Gs_t}\right)^{\gamma} \qquad (32)$$

Figure 7 plots equation (31), for three different price elasticity of demand values, and equation (32), both as a function of throughput. The optimal channel throughput per channel will vary according to individuals subjective monetary assessments of digitized voice quality as characterized by the variable β. The optimal throughput per channel will increase, as is shown in figure 7, with decreasing price elasticity of demand.

The reservation price must exceed the terminal price to induce the prospective subscriber to purchase a terminal and enter the market. This assumes certain demand, but in reality the future demand for MSAT usage will not be known with certainty. In fact, the very nature of the demand uncertainty will induce an option demand, i.e. the willingness-to-pay for the future option of communicating via the MSAT system.[33] This element of the overall demand for terminals, particularly terminals within the lower price ranges, reveals an important underlying contribution of MSAT technology to social welfare that may never show up in the actual utilization of services. Individuals will buy terminals as a form of insurance against an

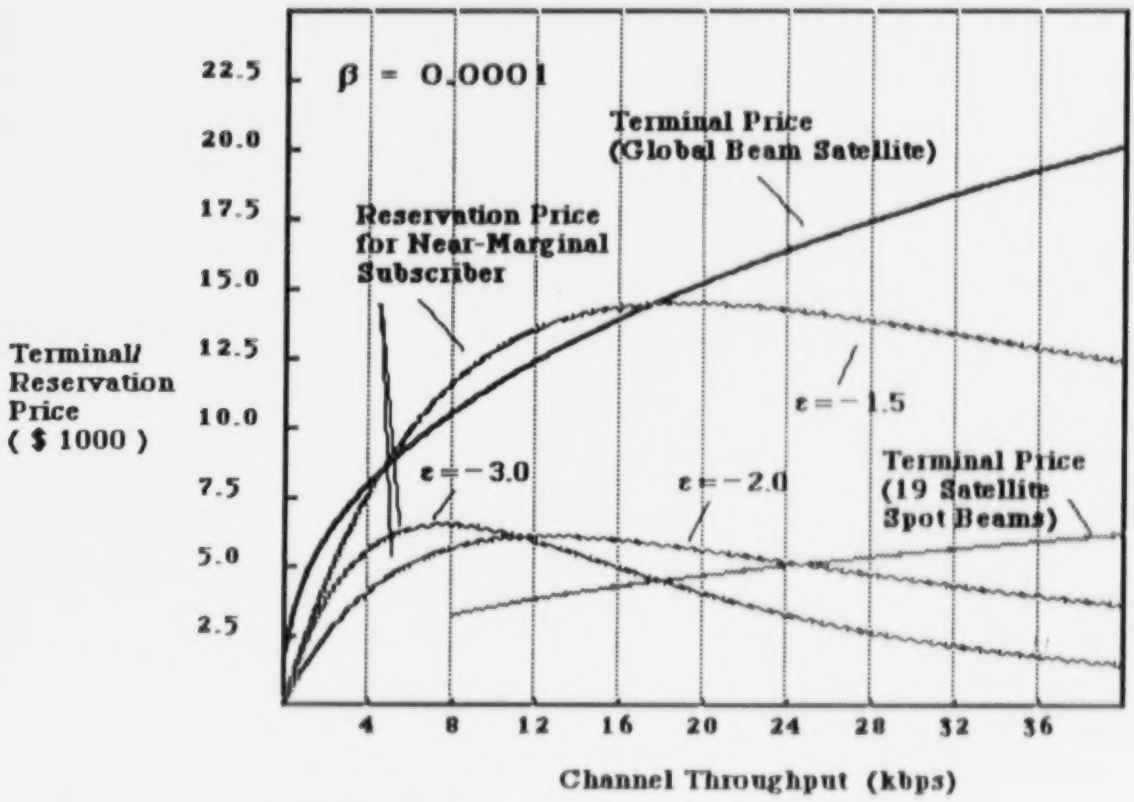


Figure 7. MSAT Terminal Price and Subscriber Terminal Reservation Price as a Function of Return Link Throughput

unforeseen but urgent need. MSAT terminals will be an excellent addition to the life-saving and emergency gear of hikers, campers, recreational boaters, and so forth.

Optimizing Terminal Antenna Gain as a Function of Usage Quantity

The optimal antenna gain for an individual subscriber will be a function of total usage demand over the economic life of the terminal. To show this it is necessary to consider the factors that determine the usage price per bit P_u. Recall the cost functions for forward and return link service capacity given by equations (15) and (16). The cost of return link service capacity is independent of terminal antenna gain, but the cost of forward link capacity is not. The usage price per bit of information transmitted over the forward link should be set in proportion to the marginal cost of service capacity.

$$P_{uF} = \Omega\left(\frac{\alpha E_T P_E}{g} + B_T P_{BF}\right) \tag{33}$$

Assuming that the subscriber forecasts future demand for usage at a level equal to I bits over the relevant investment period, the terminal purchased should have an antenna gain that solves the following cost minimization problem:

$$\text{Minimize } P_t(g) + I \cdot P_{uF} = C_t g^{\gamma} + I \cdot \Omega\left(\frac{\alpha E_T P_E}{g} + B_T P_{BF}\right) \tag{34}$$

The optimal value of g as a function of I is given by the following equation:

$$g = \left(\frac{I \cdot \Omega \alpha E_T P_E}{\gamma C_t}\right)^{\frac{1}{1+\gamma}} \tag{35}$$

This result applies for a single point (E_T, B_T) in the power-bandwidth space that was used earlier to characterize modulation and coding standards. The solution is complicated by the fact that the optimal bandwidth expansion factor B_T is also a function of g, as given by equation (10). Therefore, it is of interest to obtain a solution for g in equation (10),

$$g = \frac{B_T(2B_T - 1)P_B}{\alpha P_E} \tag{36}$$

and then substitute for E_T in equation (35) using equation (11) to obtain an expression for the optimal value of g as a function of B_T and the level of usage.

$$g = \left(\frac{-I \cdot \Omega \alpha 2B_T \ln\left(1 - \frac{1}{2B_T}\right) P_E}{\gamma C_t} \right)^{\frac{1}{1+\gamma}} \tag{37}$$

Equation (36) is plotted in Figure 8, as is equation (37) for three different levels of usage represented by three different values of I. The intersection of the curves represent the combinations of modulation and error-correction coding standards and terminal antenna gain that are optimal for the specified levels of usage.

The Selection of Service Standards

The MSAT services market that has been characterized by the foregoing discussions is a theoretical representation that may bear little resemblance to the actual market. The entrance and exit of service providers will not be frictionless, and the prospects of service and space segment factor prices ever reaching efficient equilibria may be fanciful. Furthermore, there is the unpredictability of the market for service standards. Although the process of standardization to arrive at a relatively limited set of service is inevitable, its course and conclusion are uncertain and include the prospects of socially unfavorable outcomes.

It is clear that there is no "best" standard, but there probably is an optimal set of standards that balances the welfare costs of multiple standards development with the welfare benefits of subscribers having access to services at close to their individual optimal locations in the service space. From a normative perspective, the problem of selecting optimal standards is analogous to the problem of socially optimal product differentiation. For sufficiently large returns to scale the optimal number of products is one; and for more moderate returns to scale, there should be a greater diversity of products.[34] The consumer will maximize utility through the consumption of services and, indirectly, the consumption of the associated quality attributes. Because

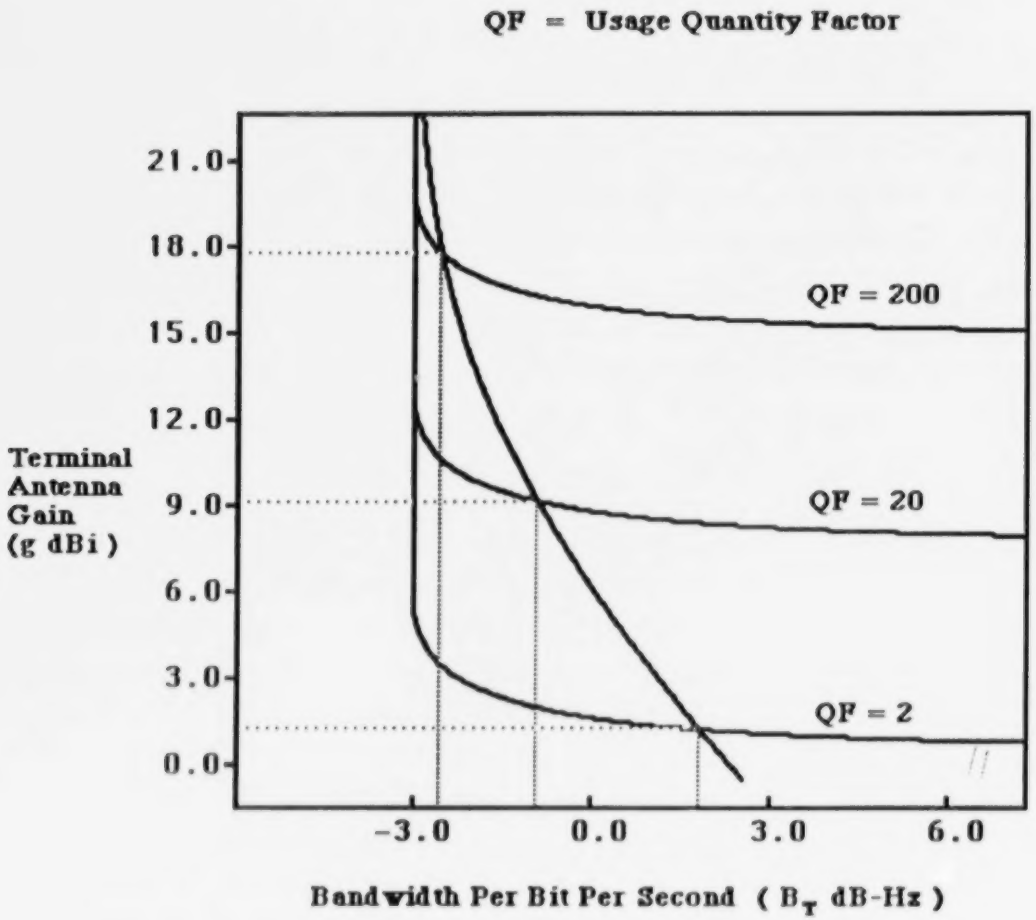


Figure 8. Optimal MSAT Terminal Antenna Gain and Coding Rate for Variations in Usage Quantity

individual consumer preferences, usage, and budget constraints will differ in general, the optimal service, defined as a location in the service or quality attribute space, will differ for each subscriber. The selection of service standards is therefore a multiattribute decision that depends on the distribution of preferences taken over the aggregated population of users. Each consumer is obliged to move from a preferred service vector to the nearest available offered service, which results in one form of welfare loss. This loss is mitigated by the introduction of a greater range of services. Service diversity leads to its own losses in the form of the increased costs of multiple service production and forgone scale economies.

The economic and institutional forces that lead to the formation of technical standards are difficult to model by positive theories. There are several paths toward standardization, each of which might eventually play a role in the MSAT industry. MSAT standards could emerge through: (1) the efforts of industry standardization committees, (2) government mandate (resulting in de jure standards), or (3) competitive market selection (resulting in de facto standards). Standards will quickly emerge in the MSAT industry whether or not the government or any other external agent exerts an influence. A principle reason is that a network externality comes into play due to the complementarity of the service and terminal markets which should quickly lead to a set of de facto standards.[35] Much as developers of software for personal computers consider operating system compatibility in their product development decisions, so would an entrant to the MSAT services industry similarly consider compatibility of the existing population of terminals. Likewise, purchasers of terminals will consider the number of compatible MSAT service offerings as a criterion for their purchase, just as personal computer purchasers are concerned with the availability of compatible software. The mutual gains to compatibility between the services and terminal market is an example of the competitive market forces which tend toward product standardization.

It appears that without the constraints of a formal open network policy, the MSAT space segment provider would exercise the greatest influence on standards in the MSAT industry. The portion of an industry where market power is most concentrated will in general have the greatest influence on the formation of standards.[36] The envisioned proliferation of MSAT terminals emphasizes the importance of service standards that must inevitably emerge, either through government mandate or the actions of industry agents. Within the MSAT industry, terminal purchases are made by a relatively uninformed public, much as radios and televisions are purchased by individuals with little knowledge of underlying technical specifications. This

contrasts with conventional satellite systems where the satellite space segment and the interoperable terminals are purchased by a single firm, and the consequences of engineering choices and changes are for the most part internal to the firm.[37] Selection of the wrong standard will result not only in welfare losses due to short term technical and economic inefficiencies, but also in future, more significant losses if the standard should ever be modified and the existing population of user terminals require a retrofit.

Summary

The approach of this paper has been to represent the MSAT services market by streamlined engineering and economic models that can be evaluated and understood by most policy decision-makers trained in basic economics. Good public policy for the organization and regulation of a particular industry is difficult to formulate even when the information available is accurate and the understanding of it solid. It is often the case, however, that decision-makers do not have the background nor the time to properly understand the issues with the greatest impact on policy. The objective of this work, therefore, has been to take a fairly novel and complex communications industry and explain it through models that are technically accurate but simplified substantially so as to provide accessible insights. It is believed that the models capture the essential economic features of the MSAT services market.

Several distinct but interrelated markets of the total MSAT industry were isolated, and their economic inputs and outputs were identified. First, the so-called space segment market was shown to be based on the production and sale of very elemental commodities: satellite power and bandwidth. The cost function for MSAT transmit power is dependent totally on the performance and cost of available satellite technology; while the cost function for MSAT spectrum is a function of both the technology and the quantity of government-allocated spectrum. The size of a specific government allocation of spectrum determines the price of spectrum as a factor input to the production of capacity. The services market is based on the utilization of space segment factors for the production and sale of services, whose description may vary significantly over several fundamental dimensions of quality (e.g. throughput, error rate, etc.) The service space is described as a continuum mainly because the optimal specification of service vectors within that space is a difficult analytical problem to solve without adequate data on consumer demand. The selection of service standards will either occur through trial and error within a competitive market, through the adoption of the

recommendations of an industry standards committee, or through direct government mandate. The market for subscriber terminals complements the services market. The optimal terminal for a given subscriber is shown to be a function of the subscriber's projected demand for usage. The price of a terminal represents a subscriber access price. If a subscriber anticipates a large amount of future usage, the most economic terminal choice is one with a large antenna gain, and vice versa.

This paper did not consider the space segment provider's problem of setting production levels and prices for transmit power and bandwidth. It is merely assumed that such prices exist, and that the service providers make the best economic choices given those prices. It is important to note that the space segment provider will produce MSAT transmit power and bandwidth in a specific ratio, depending on its forecasts of future demand. Different service standards, however, require differing ratios of transmit power and bandwidth as inputs, depending on the quantity of usage required and the type of subscriber terminal (terminal antenna gain) used. The diversity contained within the MSAT service space and the lack of a priori knowledge as to the distribution of demand over that space makes it very difficult to propose, ex ante, a set of standards that will maximize benefits at the lowest aggregate cost. The uncertainty simply cannot be overcome except through formalized elicitation of willingness-to-pay data from probable MSAT subscribers or through the delayed analysis of competitive market outcomes.

Part of the excitement of new and innovative digital communication technologies is the anticipation of service innovations springing from these technologies. Policies that are formulated with a rigid adherence to precedent and a fixed focus on familiar service sets will certainly miss this point. The policy challenge, therefore, as it has also appeared in more conventional telecommunication settings, is to provide the centralized supply of information regarding service standards necessary to bolster subscriber confidence and demand, while preserving market flexibility for the efficient emergence of innovations.

The author would like to acknowledge the frequent and helpful discussions with Marvin Sirbu, Carnegie Mellon University, Dept. of Engineering and Public Policy, which contributed to the preparation of this paper.

NOTES

1. G.H. Knouse and P.A. Castruccio (1981).
2. D. Chakraborty (1988).
3. B.G. Evans, et. al. (1987).
4. Aviation Week and Space Technology, p.47, December 7, 1987.
5. INMARSAT (1985) and (1986).
6. M. Schwartz (1987).
7. S.S. Anderson, Ph.D. Thesis, Carnegie-Mellon University, Department of Engineering and Public Policy, to be published. The existence of scale economies in satellite systems is well known.(W. Pritchard (1981), M.S. Snow (1975)) They are probably more pronounced in MSAT systems due to the influence of spot beam antennas in the production and cost functions.
8. The MSAT industry provides an interesting case for application of an open systems regulatory approach. The production of MSAT capacity is characterized by substantial scale economies, which indicates that the capacity market is in fact a natural monopoly. At the same time, the MSAT service space is for the most part unchartered. It therefore appears particularly important that regulatory policies exploit to the extent possible the efficiencies in capacity production available through scale economies while preserving incentives for innovation and efficient diversity within the services market — the same reasons that have prompted the Federal Communications Commission (FCC) to move in the direction of Open Network Architecture (ONA) for the generic telecommunications industry. Through the strategic implementation of standards for MSAT capacity contracts, the market power of the portions of the MSAT industry where huge scale economies prevail may be isolated from a competitive services market. The market for MSAT capacity is more amenable to regulatory oversight than the services market. The product is clearly defined and easily standardized without undue risk of thwarting the satisfaction of diverse consumer preferences. Furthermore, the possibility of capacity and service providers negotiating contracts for MSAT capacity rights prior to the development and launch of the satellite allows the economic risk of the venture to be shifted away from the satellite operator and distributed among the prospective service providers.
9. C.E Shannon (1949), J.M.Wozencraft and I.M. Jacobs (1967) p.323.
10. A. Viterbi and J. Omura (1979), W.W.Wu, et. al. (1987).
11. S.S. Anderson, Ph.D. Thesis. The capacity approximation is derived from a theoretical

expression known in communications theory as the channel cutoff rate. (J.M.Wozencraft and I.M. Jacobs (1967); A. Viterbi and J. Omura (1979)).

12. G.D. Forney, et. al. (1984).

13. The MSAT communications channel suffers from fast multipath fading. Complex signal constellations in the phase plane will suffer distortions and performance will quickly be undermined.

14. B.E. Collins, et. al. (1987).

15. Representative forward and return link power budgets for a global beam antenna are provided in Appendix A.

16. The unavoidable approximation used to obtain equation (8) is described as follows:

$$\frac{x}{1-x} + \ln(1-x) = \sum_{n=1}^{\infty} x^n - \sum_{n=1}^{\infty} \frac{x^n}{n} = \sum_{n=2}^{\infty} x^n - \sum_{n=2}^{\infty} \frac{x^n}{n}$$

$$\sim \sum_{n=2}^{\infty} x^n = \frac{x^2}{1-x}$$

$0 < x < 1$. The approximation overbounds the true value.

17. H.R. Varian (1984) p.10.

18. The satellite receiver noise temperature is expected to be higher than the mobile terminal noise temperature, and propagation losses will be slightly higher at the higher return link frequency.

19. H.R. Varian (1984) p.33.

20. The most likely number of frequency assignments, r, is either 4 or 7. When the number of spot beams deployed is low, r = 4 would be sufficient to prevent excessive interbeam interference. However, as the number of spot beams is increased, so must the number of frequency assignments. (A.B. Salmasi (1984)).

21. The assumption of linear incremental satellite transmit power and spot beam costs is clearly a simplified version of reality, but adequate as a first approximation. Pritchard (1981) cites a model based on econometric analyses that shows the marginal cost of satellite power to be decreasing with the level of deployed power.

22. Profits are maximized by adopting the pricing formula that equates marginal revenues to marginal cost:

$$\text{Profit maximization: } P(Q) = \frac{\frac{\partial C(Q)}{\partial Q}}{\left(\frac{1}{\varepsilon} + 1\right)} \qquad (22.1)$$

Welfare is maximized by setting price equal to marginal cost:

$$\text{Welfare maximization: } P(Q) = \frac{\partial C(Q)}{\partial Q} \qquad \therefore \quad (22.2)$$

When $\partial C/\partial Q < C(Q)/Q$, i.e. marginal costs are less than average costs, as is the case with many public utilities, the welfare maximizing solution 22.2 cannot be implemented since it would result in inadequate revenues. A profit constraint must therefore be imposed to ensure adequate revenues, and the pricing solution obtained falls into the category of "second best" quasi-optimal policies. (Crew and Kleindorfer, 1986) We assume that whichever pricing policy is adopted, the price will bear a proportional relationship to marginal cost through a constant denoted as Γ.

23. A.E. Kahn (1988), Chapter 3.
24. D Bersekas and R. Gallager (1987), a general textbook on data networks.
25. H.R. Varian (1984) Chapter 7.7.
26. S. Rosen (1974).
27. D. Chakraborty (1988) provides an overview of technical issues involved in the production of VSAT services and service quality parameters. Since much of the analysis would also apply to an MSAT system, the paper by Chakraborty is useful background for a technical understanding of the MSAT service space.
28. Channel delay is also a critical quality attribute variable for voice communications. Two round trips to and from a geosyncronous satellite produces a delay of a little more than half a second, and the impact on the quality of the voice channel is discernible. A one-second delay is definitely annoying and seriously impedes the ability for the average speaker to communicate. Minimal delays can be assured with a channel allocation scheme that assigns channels for the duration of the voice call. It will be assumed that such an allocation scheme is utilized, so the demand for and costs of reduced voice channel delay need not be considered further.

Channel bit error rate is another quality variable not considered directly in the analysis.

The subjective quality assessment of a digitized voice transmission is relatively insensitive to bit error rates up to 10^{-3}, as has been verified by numerous subjective quality tests (Daumer and Cavenaugh 1978). Error rates above this level begin to cause disturbing distortions, although some voice digitization techniques incorporate error-detection mechanisms and retain their quality at error rates above 10^{-2}. It is assumed that a bit error rate specification of 10^{-3} will apply for MSAT digitized voice communication services. Little subjective benefit is obtained by improving upon this specification, and the costs saved by increasing the bit error rate are minimal, particularly in contrast to cost variations associated with the choice of channel throughput, which may range by more than an order of magnitude.

29. W.R. Daumer and J.R. Cavenaugh (1978), W.R. Daumer (1982), Y. Yatsuzuka, et. al. (1983).
30. INMARSAT (1985).
31. A. Ghais, et. al. (1987).
32. Pritchard (1981) gives the cost of a satellite earth station as proportional to the earth station EIRP raised to a constant power.

$$\text{Cost} = K(\text{EIRP})^{0.3} \tag{31.1}$$

33. B.A. Weisbrod (1964).
34. K. Lancaster (1975).
35. M.L. Katz and C. Shapiro (1985).
36. S.M. Besen and L.L. Johnson (1986).
37. M. Sirbu and S. Stewart (1985).

Appendix A.

The following table provides representative link power budget parameters for a global beam mobile satellite system (i.e. A = 1, and n = 1).

Satellite-to-Mobile Forward Link (1540 MHz)	e = 23 dB
Satellite Transmit Power	s dBW
Misc. Losses	-3.0 dB
Satellite Antenna Gain (Global)	17.0 dBi
Space Loss	-188.0 dB
Boltzmann's Constant	228.6 dB/Hz/K
Mobile Receiver Noise Temp.	-25.6 dBK
Mobile Antenna Gain	g dBi
Assumed Eb/No Requirement	6.0 dBHz
Communications Capacity	s + g + 23 dB(bps)
Mobile-to-Satellite Return Link (1645 MHz)	**e = 19 dB**
Mobile Transmit Power	St dBW
Misc. Losses	-3.0 dB
Mobile Antenna Gain	g dbi
Space Loss	-189.0 dB
Boltzmann's Constant	228.6 dB/Hz/K
Satellite Receiver Noise Temp.	-28.6 dBK
Satellite Antenna Gain (Global)	17.0 dBi
Assumed Eb/No Requirement	6.0 dBHz
Communications Capacity	St + g + 19 dB(bps)

Table A.1 Power Budgets for Global Beam Mobile Satellite Link

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